

Comparison of SeaWiFS measurements of the Moon with the U.S. Geological Survey lunar model

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The Sea-Viewing Wide-Field-of-View Sensor (SeaWiFS) has made monthly observations of the Moon since 1997. Using 66 monthly measurements, the SeaWiFS calibration team has developed a correction for the instrument's on-orbit response changes. Concurrently, a lunar irradiance model has been developed by the U.S. Geological Survey (USGS) from extensive Earth-based observations of the Moon. The lunar irradiances measured by SeaWiFS are compared with the USGS model. The comparison shows essentially identical response histories for SeaWiFS, with differences from the model of less than 0.05% per thousand days in the long-term trends. From the SeaWiFS experience we have learned that it is important to view the entire lunar image at a constant phase angle from measurement to measurement and to understand, as best as possible, the size of each lunar image. However, a constant phase angle is not required for using the USGS model. With a long-term satellite lunar data set it is possible to determine instrument changes at a quality level approximating that from the USGS lunar model. However, early in a mission, when the dependence on factors such as phase and libration cannot be adequately determined from satellite measurements alone, the USGS model is critical to an understanding of trends in instruments that use the Moon for calibration. This is the case for SeaWiFS. © 2004 Optical Society of America

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1. Introduction

The Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) is a second-generation ocean color instrument. As such, its mission was designed in very large part on the lessons learned from its predecessor, the Coastal Zone Color Scanner (CZCS).^{1,2} Contractually, SeaWiFS was the procurement of an ocean color data set by the U.S. government, not an instrument of the government's design³; however, the performance specifications for the instrument included a requirement for direct lunar views to monitor instrument stability.³ In addition, the performance specifications called for either an internal light source or a solar diffuser as a second monitor of instrument change. The manufacturer of SeaWiFS chose to incorporate a solar diffuser. These design decisions have had a fundamental effect on the stability-monitoring program for SeaWiFS.

SeaWiFS was launched on 1 August 1997 onboard the SeaStar spacecraft (now called Orbview-2). The first images of the Earth were taken on 4 September 1997, and the first lunar measurements were made

on 14 November 1997. Since then, lunar measurements have been made on a monthly basis. The SeaWiFS calibration team does not, as yet, use the Moon as an absolute radiometric standard for calibration purposes. The Moon is used solely as a diffuse reflector whose surface remains unchanged.⁴

From the outset, the SeaWiFS calibration team did not consider itself to be expert on the surface properties of the Moon. In particular, the team was unable to account for the effects of lunar libration, in which the face of the Moon as seen from the Earth varies over time owing to a slow, periodic wobble of the Moon as it moves through its orbit. As the Moon has an inhomogeneous surface, with a pattern that can be seen from the Earth, the wobble causes a time-dependent change in the lunar irradiance. With the Moon acting as a diffuse reflector of sunlight, this change in irradiance comes from variations in the incidence and the scattering angles of the illuminating and reflected flux from its surface. For incident flux, the angles are parameterized in terms of the lunar (selenographic) latitude and longitude of the subsolar point. For scattered flux, the angles are parameterized in terms of the selenographic latitude and longitude of the subsatellite point.

With the published description of the U.S. Geological Survey (USGS) lunar irradiance model,⁵ it was recognized by the calibration team that the phase and libration factors in that model are derived empirically, that is, from observations of the Moon by the USGS telescope. As a result, the SeaWiFS calibration team has developed a set of libration corrections based on the long-term set of SeaWiFS lunar measurements. This development has been made possible, in large part, by the limitation of the SeaWiFS measurements to a small set of lunar phase angles.

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The phase angle is the angle between the Moon–Sun vector and the Moon–observer vector. The change in phase angle over a lunar month is the dominant factor in the cyclical changes in the brightness of the Moon and, therefore, in the USGS lunar model, which covers phase angles from 90° before full phase to 90° after.^{5,6} It is a much smaller factor in the SeaWiFS lunar measurements and thus greatly simplifies the analysis by the team.

In Section 2 we present the SeaWiFS measurements of the Moon, plus corrections to remove non-instrumental effects, including libration, from the lunar time series. In that section we also describe the time-dependent changes in the SeaWiFS bands derived from the lunar measurements. In Section 3 we give an overview of the USGS telescope and the lunar model based on its measurements, and in Section 4 we compare the SeaWiFS measurements of the Moon (after correction for the time-dependent changes in the SeaWiFS bands) with the corresponding values calculated from the USGS model.

5. Concluding Remarks

The SeaWiFS measurements of the Moon are independent from those of the ROLO telescope. However, the claim of independence of the two techniques must be tempered by knowledge of the similarities in the methods of analysis. Both sets of measurements apply corrections for distances and phase angles and for changes in the portion of the Moon that is observed over time. If this set of corrections is appropriate, then the agreement in the instrument response histories for the two techniques provides a validation of the USGS lunar model by SeaWiFS over the range of SeaWiFS phase angles and vice versa.

As the SeaWiFS mission continues, the understanding of the measurements also continues to develop. As of this writing in 2004, the SeaWiFS project has completed its fourth update of the data set with a reprocessing in July 2002.³¹ A fifth reprocessing of the data set, in 2005, is anticipated. Before the July 2002 reprocessing, long-term instrument changes in the data set were based on the assumption that, on average, the 490- and 510-nm bands were not changing over time.^{8,14} We calculated the changes in the other instrument bands by normalizing the output of each band to the average of the 490- and 510-nm bands.^{8,14} In early 2002 a comparison was made with a preliminary version of the USGS lunar model. Based on that comparison, an average change rate of 0.35% per thousand days for those two bands was incorporated into the fourth reprocessing as a substitute for the earlier assumption.³¹ Changes for the individual bands were determined by the same normalization to the 490- and 510-nm bands. At that time, the inability of the SeaWiFS calibration team to correct the libration-based oscillations in the lunar data set precluded an independent determination of instrument changes. With the developed understanding of libration presented here it is now possible to determine the changes in each SeaWiFS band without the need for the USGS lunar model as a refer-

ence. Also, the instrument changes presented here are nearly identical to those from the fourth reprocessing. The average of the linear change rates for the 490- and 510-nm bands in Table 1 is 0.32% per thousand days.

A developed understanding of libration and other factors in a lunar time series comes from the analysis of an extended data set. The results presented here are based on 66 lunar measurements by SeaWiFS. For satellite instruments at the beginning of on-orbit operations, when the number of lunar measurements is limited, the USGS model is critical to an understanding of instrument trends that use the Moon for calibration.

For ocean color measurements the determination of instrument changes at the level presented here is important. The ocean is dark, and most of the top-of-the-atmosphere radiance over oceans comes from the atmosphere. Thus the calculation of the radiance leaving the ocean surface from top-of-the-atmosphere measurements comes from the small difference between two large numbers. Small changes in the calibration of the satellite instrument can cause large changes in the water-leaving radiances, with a multiplying factor of ~ 10 . The deep ocean gyres, where the water is clear and the chlorophyll concentrations are small, provide sensitive locations for monitoring instrument changes. Over periods of several years or more, the conditions of the gyres are not expected to change, nor are the average water-leaving radiances.³² With the current lunar-based determination of the calibration history of SeaWiFS, the trends in the global mean clear-water water-leaving radiances measured by SeaWiFS are less than 0.5% per thousand days.³¹ The assumption of no long-term geophysical change in the deep oceans is central to the interpretation of this result. For satellite calibration purposes, however, the lunar surface is photometrically stable over the period of 10^8 years.⁴

The libration corrections presented here are not part of the latest processing of SeaWiFS (Reprocessing 4, July 2002). Other changes from Reprocessing 4 include calculation of the illuminated fraction of the Moon and of the along-track size of the Moon in Eq. (4). It is anticipated that these changes will be incorporated into the next SeaWiFS reprocessing. Also, the fitted forms for the time-dependent changes in SeaWiFS bands 3–5, 7, and 8 in Eq. (6) differ from the form for instrument change in Reprocessing 4, in which each band was treated as a single exponential.³¹

At the time of the fifth SeaWiFS reprocessing there will be an expanded set of lunar measurements available for analysis. In addition, it may be possible to incorporate the efficiencies of the USGS computational technique given in Eq. (10) into the SeaWiFS libration correction. The form of Eq. (10) that uses the lunar irradiance in logarithmic space provides a potentially improved method for calculating the SeaWiFS libration coefficients compared with the current multiplicative technique. However, these changes should not affect the overall agreement of the SeaWiFS measurements with the USGS lunar model.